SEDIMENT TRANSPORT RATES AND SEDIMENT DISTURBANCE DUE TO SCALLOP DREDGING IN PORT PHILLIP BAY

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The firstdirect measurements of turbidity caused by scallop dredging are presented. The physical effects of scallop dredging on the sediment dynamics of an enclosed, heavily-fished bay in southern Australia are indicated and data are provided to assess potential biological impact. Transport and deposition of sediments were measured within and beyond the sediment plume behind a scallop dredge. Natural suspended sediment concentrations were recorded with a bottom-mounted instrumented frame; sediment disturbance behind dredges was determined using the same instrumentation mounted on a towed sled. Concentrations in the sediment plume 2-16 seconds after dredging were 2-3 orders of magnitude higher than natural concentrations. Plume concentrations were similar to the natural levels after c. 9 minutes. Thus, for typical currents of approximately $0.1 m.s^{-1}$, suspended concentrations above natural levels were confined to a region within c.54m of the dredge. However, the fine material remained in suspension longer, so dredging may be partially responsible for re-distribution of fine sediments in the bay.

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Scallop dredging is the most valuable commercial fishery in Port Phillip Bay with annual harvests worth up to $20 million. In a typical year dredges disturb approximately $400 km^2$ (20%) of the bed of Port Phillip Bay (Parry, unpubl. data). Thus, after a season of fishing, dredging represents a potential disturbance to sediment which may be equivalent to natural phenomena, particularly in deeper water where bottom wave energies are lower. By suspending the surface layer of sediment, dredging may be responsible for disturbance of previously buried material. Direct disturbance of fine sediments may result in the release of heavy metals, nutrients or toxic algal spores. Alternatively, dredging may simply break natural sediment bonds, allowing more suspension to occur during natural storms. Grain size and natural turbulence levels in the bay will determine where the sediments settle again.

This study tests whether dredging alters turbidity in the Bay and examines sedimentation patterns after a dredge passes through a region. To develop an appropriate quantitative comparison, both the natural and the dredge- related sediment concentrations were recorded. We are concerned with the physical sediment transport processes only; turbidity in the plumes, sedimentation, depth of disturbance and changes to the natural bonds in the sediments. Other factors such as incidental mortality of scallops and other marine organisms, impact on habitat and short to medium-term impacts on biological communities were treated separately; the latter is presented elsewhere (Currie & Parry, this memoir).

Currents can be tidal, wind-driven, forced from Bass Strait or associated with internal density structure (Environmental Study of Port Phillip Bay,1973; Black,1993). Wave orbital motion which determines sediment transport rate is a function of water depth, wave height, wave period, wind strength and wind fetch. Grain sizes of suspended sediments during storms vary across the bay and decrease with distance above the bed. Sediment concentrations in suspension are also a function of the cohesiveness of the sediments, and cohesiveness may be reduced after dredging.

To cater for the wide range of natural conditions, measurements of natural sediment dynamics required simultaneous time series of forcing factors, including current strengths and wave activity, and the grain size distribution of bed sediments. Natural sediment concentrations and hydrodynamic variables were measured continuously with *in situ* bottom-mounted instruments, which were deployed for periods of several days to several weeks at three sites in the bay. These measurements complemented an existing numerical hydrodynamic model of the Bay (Black et al.,1993) and earlier sediment transport and wave studies (Black & Rosenberg,1992).

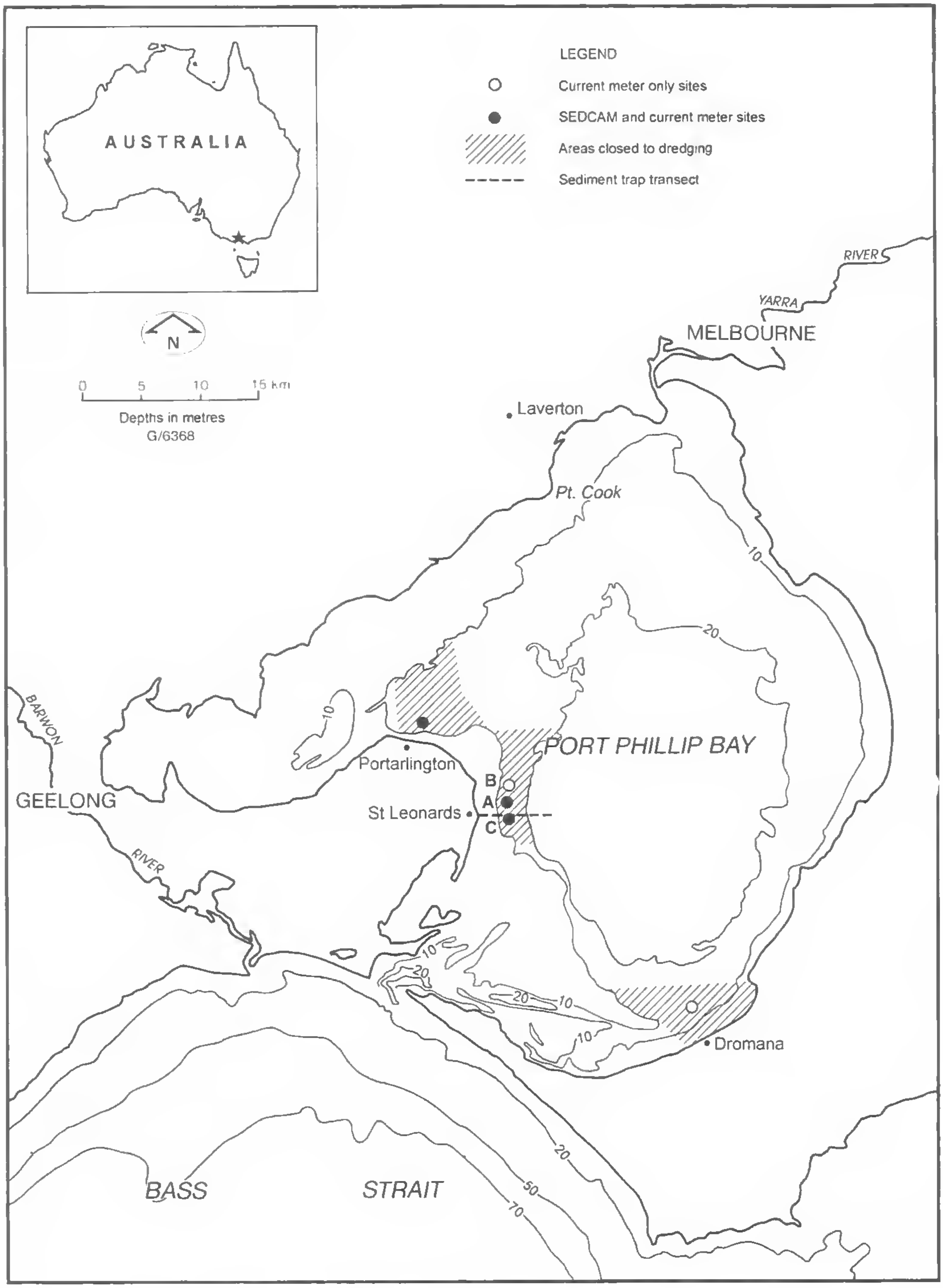

FIG.1. Study region where instruments were deployed. The experimental plots are shown at Dromana, Portarlington and St Leonards.

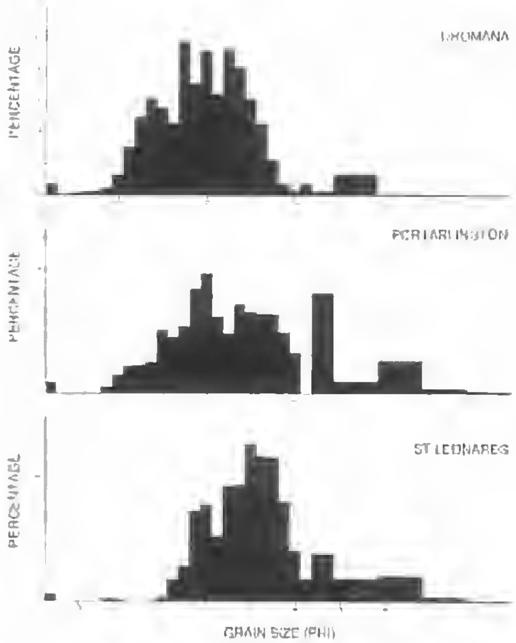

FIG.2. Representative bed sediment grain sizes at 3 study sites.

Measurements within the sediment plume of a scallop dredge required development of a towed monitoring sled. The sled was instrumented with turbidity monitors and pumps, the latter to sample for grain size and to calibrate turbidity monitors.

The overall study forms part of a series of linked biological and physical investigations, commenced in 1991 in response to a Victorian Government initiative (Parry & Currie,1992; Currie & Parry, this memoir). The objectives were to: 1) compare quantities of sediment put into suspension by scallop dredging with natural sediment transport due to storms; 2) develop a sled-mounted monitoring system to be towed behind a scallop dredge to determine the amount of sediment disturbed by dredges of different design, the influence of vessel speed, cable length and sediment type on the amount of sediment disturbed and catch efficiency of dredges of different designs, the optimal compromise between the catch efficiency and sediment disturbance; and 3) determine sedimentation patterns and areas of influence arising as a consequence of suspension of sediments by scallop dredging.

In this paper, we describe the scope of the overall study, and present results associated with the first objective and aspects of the second.

STUDY REGION

Port Phillip Bay (PPB) is a large, semi-enclosed, predominantly tidal embayment linked to the ocean by a narrow, rocky entrance (Fig.1). The surface area of the Bay is $1.95x10^9m^2$, with a tidal prism of $9.4x10^8m^3$ and a mean depth of 12.8 m (Environmental Study of Port Phillip Bay, 1973).

The hydrodynamics are characterised by (i) an entrance region where fast ebb and flood jets (of the order $3m.s^{-1}$) dominate the circulation, (ii) a flood-tidal delta, known as the Sands region, where strong currents occur in the major channels and (iii) a large 'inner' region, where tidal flows are weak (with an average of $c.0.06\ m.s^{-1}$) (Black et al.,1993). These circulation patterns are broadly reflected by sandy bottoms in the faster flowing regions and fine muds deposited in the centre of the Bay. Sandy beds which predominate around the margins reflect local wave activity.

Three commercially-dredged sites at Dromana, Portarlington and St Leonards were selected for the study (Fig. 1). Each site was located at a similar depth (c.15m) in the 'inner' region, but sites had different bed sediments and were exposed to different current strengths and wave attack.

At Dromana, bed sediments were dominantly medium-fine sands with mean grain size (Table 1). A coarse fraction (0–1phi; 0.5–1mm) was also present (Fig.2). At Portarlington, bed sediments were muddier (30.1% <63μm, Table 1) but the sediments also contained large numbers of shell fragments and the overall mean grain size was

TABLE 1. Mean grain sizes, percentage mud and sand, and spring tidal currents at the field sites. The standard deviations (SD) and the number of observations (N) are given.

Site	Mean grain size				Mud content			Spring tidal current (m/s
	(mm)	(phi)	SD (phi)	N	(%)	SD	N	
Dromana	0.22	2.17	0.33	3	7.2	2.2	29	c.0.11
Portarlington	0.14	2.82	0.44	4	30.1	6.7	44	0.11
St Leonards	0.09	3.43	0.16	7	15.3	5.7	120	0.20

TABLE 2. Scope of field study and techniques applied at Dromana (Drom), Portarlington (Port) and St Leonards (StL). The symbols show: '+' technique applied; '-' not applied; 'P' planned.

Technique applied	Drom	Port	StL
Experimental dredging	+	+	+
Sediment traps			
–natural conditions	-	+	+
–during dredging	+	+	+
Depth rings	+	+	+
SEDCAM			
–natural conditions	-	+	+
–during dredging	-	+	+
Currents	+	+	+
Waves	+	+	+
Sea levels	—	+	-
Sediment monitoring sled	+	P	P
Sediment analyses			
–natural suspended	-	-	+
–bed sediment	+	+	+
–dredge plume	+	P	P
Comparison of dredges	-	-	P

0.14mm. St Leonards sediments were predominantly fine and very fine sand (Table 1). The coarse fraction noted at Dromana and Portarlington (<1phi; >0.5mm) was absent at St Leonards (Fig.2).

Spring tidal currents are slower at Dromana and Portarlington than at St Leonards (Table 1). Dromana is the most exposed to wave attack and Portarlington the most sheltered (Fig. 1).

FIELD MEASUREMENT TECHNIQUES

The investigations adopted a wide range of techniques (Table 2) including some novel approaches.

Dredging of Experimental Plots

Experimental plots were established within large areas (20–30km^2, Fig.1) closed to all scallop dredging during 1991. Supervised dredging of these experimental plots by commercial scallop fishermen was undertaken as part of a series of controlled experiments designed to measure the effect of scallop dredging on biological communities (Currie & Parry, this memoir), bedform topography, sedimentation rates and turbidity.

FIG.3. *In situ* sediment transport unit (SEDCAM). The underwater video camera and the sediment sensor electronics are within the large housing. The smaller housing contains a battery power supply for the equipment and underwater lights. An acoustic pinger (foreground) is included to assist retrieval, if the frame was accidentally moved by a fishing boat.

TABLE 3A. The location and recording times for current meters and tide gauges deployed in Port Phillip Bay, 1991. All times are Australian Eastern Standard Time (AEST). Water depths are not corrected for tidal level at time of depth sounding. For recording intervals for S4 meters, SRB = special record blocks. For the measured parameters, V=current velocity (i.e. speed and direction and/or E/W and N/S components); T=temperature; C=conductivity; I=vertical tilt of instrument; P=pressure (a coarse value only); D=fine resolution pressure. The location of sites is shown in Fig. 1.

SITE	INSTRUMENT	MEASURED PARAMETERS	LAT./ LONG.	WATER DEPTH(m)	HEIGHT ABOVE BED (m)	DEPLOYMENT TIME		RECORDING TIME		RECORDING INTERVAL
						Mooring deployed	Mooring recovered	First record in water	Last record in water	
CURRENT METERS										
St L A	S4	V,C,T,P,I	38° 10.006'S 144° 44.74'E	14.0	3.03	16:00 29/04/91	14:46 05/06/91	23:15 29/04/91	14:00 05/06/91	1 sec. av. for 1 min. every 45 min. SRB every 90 min.
St L B	S4	V,C,T	38° 08.817'S 144° 44.926'E	13.5	2.43	14:58 24/06/91	16:20 02/07/91	15:00 24/06/91	21:45 01/07/91	1 sec. av. for 1 min. every 15 min. SRB every 15 min.
St L C	S4	V,C,T	38° 10.534'S 144° 44.883'E	14.5	2.80	13:46 15/07/91	15:22 17/08/91	00:00 16/07/91	15:00 17/08/91	2 sec. av. for 1 min. every60 min. SRB every 120 min.
DROM	S4	V,C,T	38° 18.843'S 144° 56.410'E	14.5	2.80	09:55 26/08/91	12:10 02/09/91	10:00 26/08/91	11:30 02/09/91	2 sec. av. for 1 min. every 30 min. SRB every 120 min.
PORT	S4	V,C,T,P,I	38° 05.964'S 144° 40.910'E	14.0	2.70	12:09 15/11/91	14:10 18/12/91	14:00 15/11/91	14:00 18/12/91	1 sec. av. for 2 min. every 120 min. SRB every 120 min.
PORT	NEIL BROWN	V,T,I	38° 05.964'S 144° 40.910'E	14.0	6.10	12:09 15/11/91	14:10 18/12/91	12:20 15/11/91	14:10 18/12/91	Vector av. every 10 min.
TIDE GUAGE										
PORT	AANDERAA	D,T	38° 05.964'S 144° 40.910'E	14.0	0.75	12:09 15/11/91	14:10 18/12/91	12:15 15/11/91	14:00 18/12/91	15 min.

Experimental plots were 600x600m at Dromana and Portarlington and 600mx750m at St Leonards (Rosenberg et al.,1992). All plots were dredged with the same intensity and dredging was continued until the entire plot had, on average, been passed over twice by a scallop dredge. The Portarlington plot was dredged with this intensity on two occasions, three weeks apart. To achieve the desired intensity of dredging, 5–7 commercial scallop boats worked each plot over 2–3 days. Dredging was always restricted to approximately 3 hours per day when tidal currents were flowing strongly in the direction of downstream instrumentation. Relevant parameters were measured by locating turbidity sensors, a current meter and sediment traps downcurrent of the experimental plots.

Currents and Tides

Currents and wave orbital motions were measured using an S4 electromagnetic current meter deployed on a mooring (Table 3A). These vector-averaging meters are suitable for combined wave and current environments. Sea levels were normally taken from permanent stations around the bay at Williamstown, Geelong and Pt

TABLE 3B. The location and recording times for video camera and sediment sensors deployed on SEDCAM in Port Phillip Bay, 1991. All times are AEST. Depths not corrected for tide at time of sounding. The location of sites is shown in Fig. 1.

VIDEO							
SITE	LAT./ LONG.	WATER DEPTH (m)	DEPLOYMENT TIME		RECORDING TIME		RECORDING INTERVAL
			Mooring deployed	Mooring recovered	First record in water	Last record in water	
St L A	38° 10.000'S 144° 44.737'E	14.0	15:30 29/04/91	14:30 05/06/91	23:00 29/04/91	07:00 05/06/91	1 min. burst every 8 hrs
St L C	38° 10.528'S 144° 44.883'E	14.5	13:30 15/07/91	15:10 17/08/91	16:00 15/07/91	08:00 17/08/91	1 min. burst every 8 hrs
PORT	38° 05.970'S 144° 40.910'E	14.0	12:20 15/11/91	14:04 18/12/91	16:00 15/11/91	08:00 18/12/91	1 min. burst every 8 hrs

SEDIMENT SENSORS								
SITE	LAT/LONG	WATER DEPTH (mm)	LEVEL ABOVE BED (m)	DEPLOYMENT TIME		RECORDING TIME		RECORDING INTERVAL
				Mooring deployed	Mooring recovered	First record in water	Last record in water	
St L A	38° 10.000'S 144° 44.737'E	14.0	0.11/ 0.41	15:30 29/04/91	14:30 05/06/91	00:02 30/04/91	14:14 05/06/91	3min. av. of 30sec. scans for 18 min. every hour
St L C	38° 10.528'S 144° 44.883'E	14.5	0.15/ 0.30	13:30 15/07/91	15:10 17/08/91	00:01 16/07/91	15:07 17/08/91	3min. av. of 30sec. scans for 18 min. every hour
PORT	38° 05.970'S 144° 40.910'E	14.0	0.15/ 0.35	12:20 15/11/91	14:04 18/12/91	00:04 16/11/91	14:04 18/12/91	4 min. av. of 1min scans for 20 min. every hour

Lonsdale. An Aanderaa WLR5 tide gauge was deployed at Portarlington where tidal constants and low frequency sea level measurements were needed (Table 3A).

Tidal analyses, using the procedure of Foreman (1977), were applied to each current meter and tide gauge time series. The tidal components could then be subtracted from the raw time series, leaving a residual current or sea level for separate analysis.

In Situ Sediment Recording Instrumentation (SEDCAM)

Sediment transport rates under natural conditions and during experimental dredging were measured with SEDCAM (Fig.3), a free-standing aluminium frame upon which were mounted a Sony Video 8 camera, underwater lighting and 2 infra-red backscatter turbidity sensors (D&A Instruments; Downing et al., 1981). All instruments were mounted high enough to minimize any disturbance to the bed. The camera was placed c.60cm above the bed. Filming was close enough to the bed to view the onset of sediment entrainment. Operating for 1 minute every 8 hours, up to 60 days of unattended operation was possible with a 3-hour film.

In conjunction with the adjacent current meter, SEDCAM enabled determination of the sediment threshold *in situ* (with undisturbed sediments) by inspection of the video film of the sea bed and current meter measurements. SEDCAM also records long-term variation in suspended sediment load. The equipment was originally developed for studies of sediment movement in wave/current environments in eastern Bass Strait (Black et al. in press).

The turbidity sensors were electronically controlled and powered from within an underwater housing so that no link to the surface was required. A bank of 6V rechargeable gel-cells powers the system for up to 6 weeks. Turbidity measurements were recorded at 30 or 60 sec intervals and averaged every 3–4 minutes (Table 3B) using a 4-channel 128K Wesdata 692 data logger.

The turbidity sensors were initially set 0.15–0.45m above the bed. Divers checked the exact elevations once the frame had settled into the sediments (Table 3B). Calibration of the sensors

FIG.4. Bed sediment trap.

was essential (Appendix). SEDCAM and an adjacent current meter were deployed 80 and 60m downcurrent of the nearest boundary of the experimental plots at Portarlington and St Leonards respectively. Equipment was deployed for 33 days at Portarlington and twice at St Leonards for 38 and 33 days respectively (Table 3B).

Turbidity sensors were regularly cleaned by divers to eliminate any marine fouling. However, the large amount of drifting seaweed and the activity of fish resulted in some interference with the sensors, particularly at St Leonards. Anomalous data were obvious from the exceptionally high readings and so these data could be detected in the final calibrated time series.

Sediment Traps

Sediment traps were used in addition to the turbidity sensors to estimate time-integrated sedimentation rates in natural conditions and during dredging. Traps are particularly useful for examining relative deposition rates; any alterations to flow characteristics resulting from the

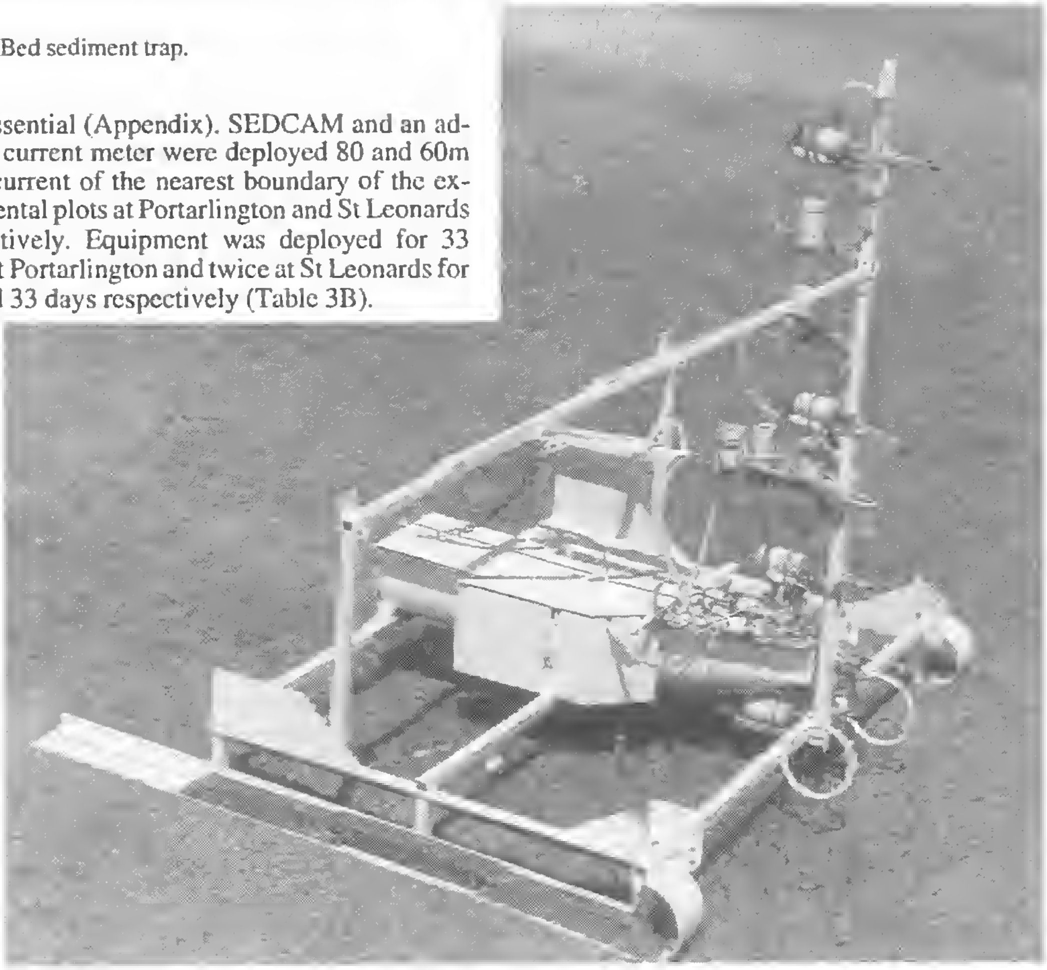

FIG.5. The sediment monitoring sled. Water pumps and turbidity sensors are placed on the upright at the front of the sled. The controlling electronics are located in an underwater housing within the metal protective container on the sled. Hoses terminate in metal housings where water samples are collected in plastic bags.

FIG.6. 'Depth rings' being placed in the bed to measure depth of sediment disturbance by scallop dredges.

traps themselves should affect all traps similarly. The traps record the total amount of sediment deposited during a storm or during dredging. Unlike the natural condition when sediment is continuously entrained and deposited, sediment entering a trap is not re-suspended. Accordingly, the actual net deposition during a storm will be less than that inferred from the trap results.

Each sediment trap consisted of twelve transparent acrylic tubes (70mm diameter x 350mm height) standing vertically in a plastic crate (Fig.4). The crate was normally placed on the bed by a diver (hence sampling occurred at 0.35m). Additional traps, sampling at elevations of 0.5, 1.0 and 2.0m, were placed on a supporting metal frame at the Portarlington site to examine vertical variation in sediment concentration and grain size.

Sediment traps were placed 30, 60, 90, 200 and 400m downcurrent from the experimental plots, as well as at two 'control' sites located up-current. Traps were deployed just prior to the dredging, and removed as soon as possible after dredging was complete. To investigate the relationship between natural deposition and water depth, bed sediment traps were also placed along a transect perpendicular to the shoreline at St Leonards in depths of 10–23m (Fig.1).

Sediment Monitoring Sled

Sediment disturbance due to scallop dredging was measured using a towed sled designed for the study (Fig. 5). Automated infra-red turbidity sensors and electric water pumps were attached at 0.25, 0.50, 1.14 and 2.00m above the bed and towed successively at 5, 20 and 50m behind the dredge. All instruments were electronically controlled on the sled so that no electrical link to the surface was required.

Turbidity sensors continuously-recorded the sediment concentrations during dredging operations. They provided a record of the sediment concentrations as a function of elevation above the bed and after different elapsed times, in accordance with the towing distance and boat speed. Thus the measured concentration decay rate (and the changing sediment grain characteristics) enable determination of contours showing sediment deposition behind the dredge.

Pumped samples of 2.5-3.5l of fluid were taken adjacent to each of the turbidity sensors for calibration. Pumps were controlled by a time-delay magnetic switch, triggered at the surface immediately before lowering the sled to the sea bed. Pumps operated for 30sec after a delay of 4mins. Water sample bags, placed inside metal housings on the sled, were replaced when the sled was brought to the surface after each calibration run.

Multiple boat speeds and depth to cable ratios were tested while catch efficiency was also monitored. The full range of calibration samples (from each level, at each distance behind the dredge, for each of the three measurement sites) are being collected. We present the results from trials at Dromana.

Depth of Disturbance

Colour-coded 'depth rings' were used to determine the depth of bed sediment disturbed by scallop dredges. Steel rings of 70mm diameter were placed on the sea bed (excluding St Leonards) and inserted 20, 40, 60 and 80mm below the surface using a special tool (Fig.6). 33–38 of these sets of rings were placed at 3–4m spacing diagonally across the dredge path before each experimental plot was dredged. The colour and number code allowed observers on each vessel to identify the rings caught by dredges.

Position Fixing and Weather Data

Instruments were deployed from the 20m research vessel 'Sarda' and located using a satellite Global Positioning System (GPS). This was a Furuno GP500 connected to a colour video plotter. Hourly winds were taken from an exposed anemometer on a low headland at Point Cook (Fig.1). Barometric pressure and rainfall (3hr intervals) were obtained from Laverton (Fig.1).

Nature of the Bed

Bed sediment samples were collected by divers using plastic corers, driven in by hand. In addition, replicate $0.1m^2$ Smith-McIntyre grab

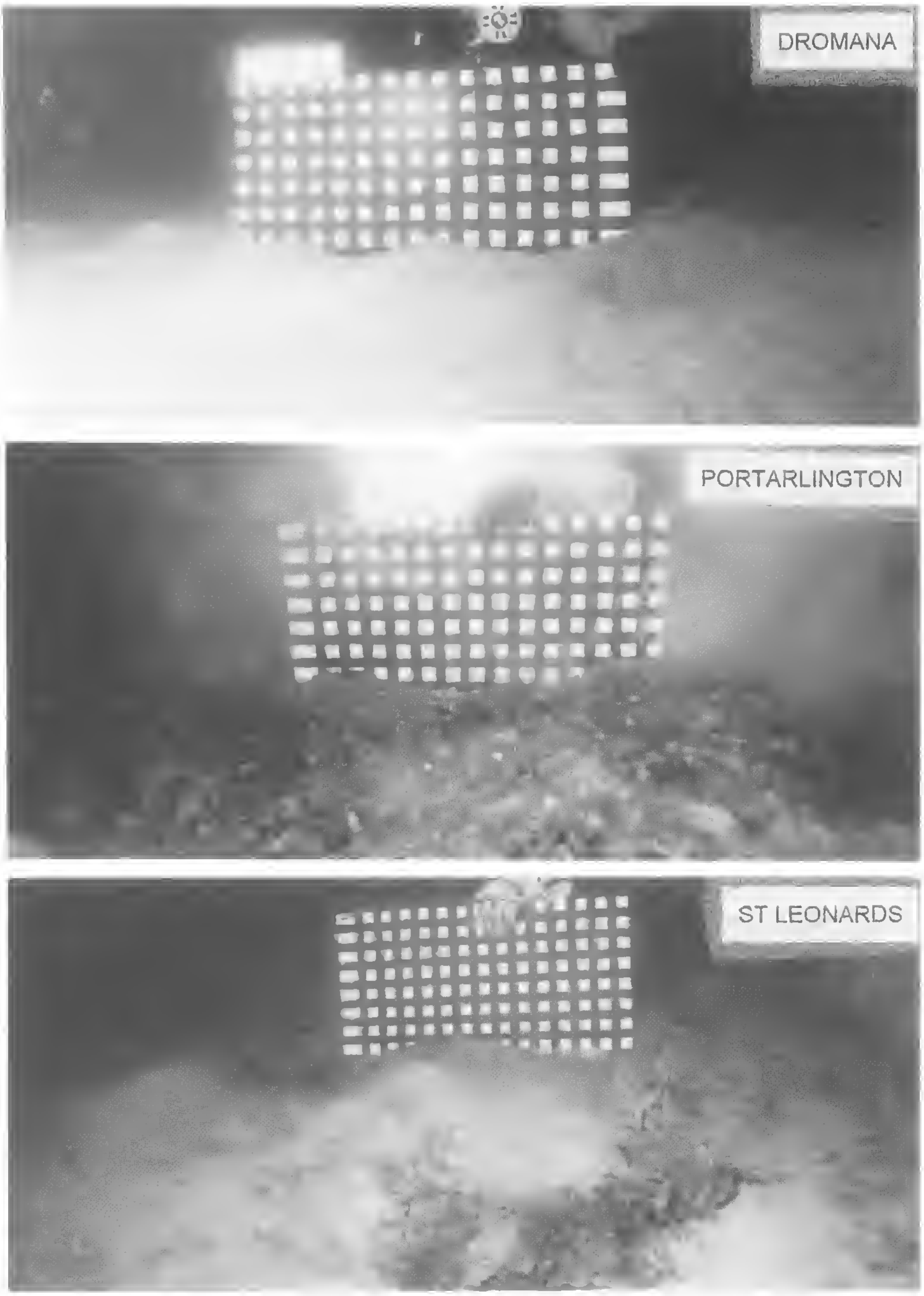

FIG.7. The sea bed at Dromana, Portarlington and St Leonards. The scale board is gridded at 2 cm intervals.

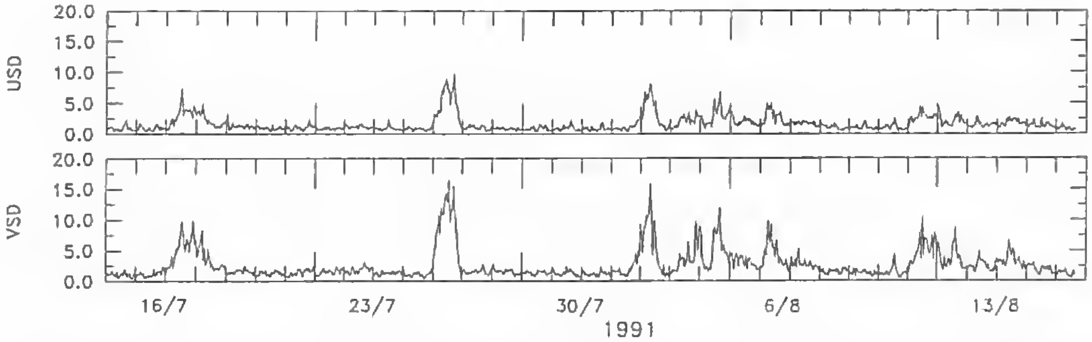

FIG.8. Wave orbital motion time series at St Leonards (Deployment C). USD and VSD are respectively the east/west and north/south components of the standard deviation of the wave orbital motion.

samples were taken at random within the experimental plots and 70ml subsamples taken for sediment analysis.

Diver-operated underwater video and underwater still (Fig.7) photography recorded appearance of the sites. The dredged and adjacent sites, plus a control site, were filmed before and after dredging. (High turbidity prevented pre-dredge filming at Portarlington.).

Fall Velocity and Equivalent Grain Size

Bed sediment, sediment trap and dredge plume samples were analysed for fall velocities and equivalent grain sizes. Percentage sands and

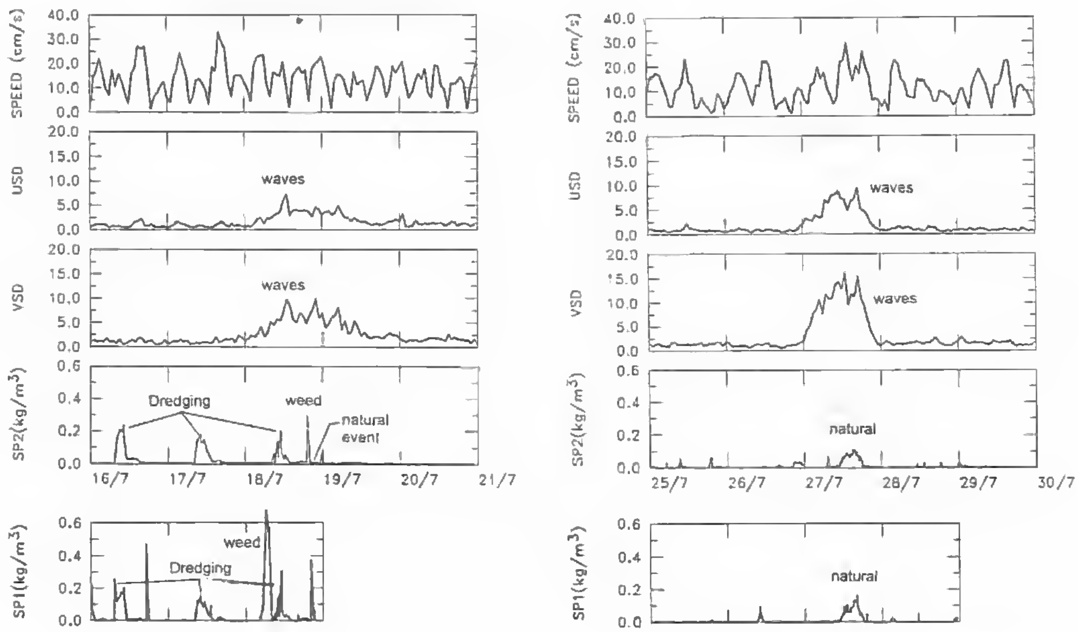

FIG.9. A, Measured currents (SPEED), bed orbital motion (USD and VSD), and suspended load (SP1 and SP2) at St Leonards C. The SPEED is the total current speed. USD and VSD are respectively the east/west and north/south components of the standard deviation of the wave orbital motion. SP1 and SP2 are the suspended sediment loads at 0.15 and 0.30 m above the bed respectively

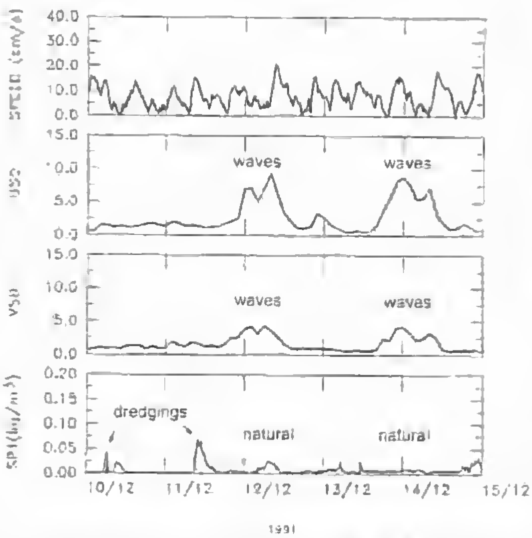

FIG. 9B. Measured currents (SPEED), bed orbital motion (USD and VSD), and suspended load (SP1) at Portarlington (Deployment E). The SPEED is the total current speed. USD and VSD are respectively the east/west and north/south components of the standard deviation of the wave orbital motion. SP1 is the suspended sediment loads at 0.15 above the bed.

muds were obtained by collecting the mud fraction on a 63μm filter. Fall velocities and equivalent grain sizes of the sand component were measured in an automated settling tube controlled by a Macintosh computer with software from the University of Waikato (de Lange, pers. comm.; Black & Rosenberg,1991).

Pipette analysis was used for the muds (Tucker,1988) and, to prevent destruction of the flocculated grains, all mud samples were kept and analysed in sea water. Using split sediment samples, fall velocities were much slower in fresh than in sea water.

RESULTS

Currents and Waves

Tidal currents, disrupted by storms, dominated the circulation at the 3 sites. However, the tidal and wind-driven currents were usually insufficient to suspend sandy sediments at the sites on their own. Additional wave orbital currents were usually needed to initiate suspended sediment transport. Peaks in the wave orbital currents (Fig.8) occur every 7–10 days in synchrony with the passage of high and low pressure systems at these latitudes. The magnitude of the peaks near the bed was determined by the water depth, wind strength and wind direction. The latter determined the wind fetch and the resulting surface wave height.

Natural Concentrations

At St Leonards natural suspended sediment concentrations during the data collection period were up to c.0.1kg.m^{-3}, although concentrations of c.0.02kg.m^{-3} were more common (Fig.9A). Similarly concentrations at Portarlington were c.0.02kg.m^{-3} (Fig.9B).

The wind strengths during the measurement periods were well above average (Fig.10). One NNE wind exceeded 17m.s^{-1} at Pt Cook which is above the 98 percentile of all measurements made over the period October 1987 to April 1989. Although this wind has one of the longest fetches in the bay for the St Leonards site, the measured suspended suspended load at St Leonards during this extreme event was $<$0.1kg.m^{-3}. Similarly the wind strengths at Portarlington during the measurement period were commonly between 10–15 m.s^{-1} and blowing across some of the longest fetches. Thus, the measured suspended loads are likely to be near the upper limit of the natural levels.

Concentrations Downcurrent of the Experimental Dredging Plots

Concentrations recorded downcurrent of the nearest boundary of experimental dredging plots were up to 0.2kg.m^{-3} at 60m from the St Leonards plot and up to 0.07kg.m^{-3} at 80m from the Portarlington plot (Fig. 9A,B). Using the measured velocities and assuming 60 and 80m excursions of the plume, the dispersal times (between dredge disturbance and measurement of the plume concentrations downstream) range from 6 to 8 minutes at St Leonards and from 10 to 25 minutes at Portarlington (Fig.9A,B). After this time, the plume concentrations were about one order of magnitude greater than the common natural values of 0.02 kg.m^{-3}.

Measurements directly behind the dredge are available for Dromana only. There, concentrations reached nearly 60kg.m^{-3} 5m behind the dredge; c.20 kg.m^{-3} at 20m; and 12kg.m^{-3} at 50m (Fig.11). For a boat speed of 3ms^{-1}, the distances represent elapsed times after disturbance by the dredge of 1.7, 6.7 and 16.7secs.

Comparison of Dredge-related and Natural Suspended Sediment Loads

Sediment concentrations 17secs after disturbance are 2–3 orders of magnitude higher than the

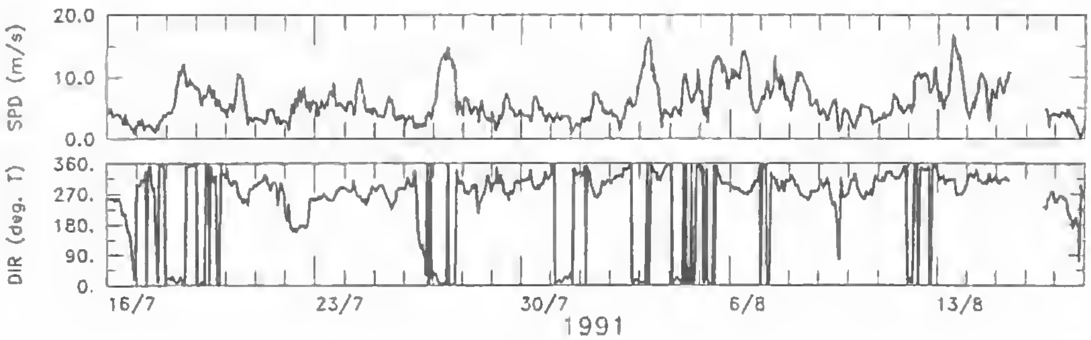

FIG.10. Wind speeds and directions measured at the Environment Protection Authority's Point Cook station during the St Leonards deployment.

natural levels. The dredging-related concentrations return to natural values recorded during large storms after about 9 minutes. However, they remain about an order of magnitude greater than the more commonly recorded storm levels. The elapsed time of 9 minutes is equivalent to 54m from the dredge for prevailing current strengths of $0.1m.s^{-1}$. Thus, elevated concentrations (equivalent to large storm events) and high sedimentation rates are restricted to within about 54m of the dredge.

Deposition Rates

Fall velocities (calculated assuming quartz density in 20°C water) for the 30th, 50th and 70th percentiles of the bed sediment grain size distribution for Dromana are 0.053, 0.039 and 0.027 m/s^{-1} respectively. The measurements indicate a maximum plume elevation above the bed of about 2m. A simple calculation serves to explain the above results although more concise numerical modelling is being undertaken to treat the full grain size distribution. In the absence of any turbulence, the times for sediment to fall out of suspension from 2m above the bed would be 37, 51 and 74secs for the 3 fractions noted above. The turbulence behind a dredge would have the effect of increasing these times. However, the calculation demonstrates that most sediment would fall out of suspension within tens of metres behind the dredge in currents of order $0.1m/s^{-1}$, even though fine material may remain in suspension for much longer times.

Depth of Disturbance

The depth of disturbance by dredges at the 3 field sites was indicated by the number of rings captured from each depth within the sediment (Table 4). While the overall capture rate was low, highest numbers were collected from the surface and the rings indicated that the maximum depth of disturbance was 60mm at St Leonards and 40mm at Dromana and Portarlington. The results suggest that the dredges dig further into the softer sediments at St Leonards than in the coarser sandier sediments at Dromana. The relatively low surface capture rates at Portarlington remain unexplained.

The depth rings suggest that the 'Peninsula' dredge commonly-used in Port Phillip Bay typi-

TABLE 4. Number of depth rings recovered from each depth during experimental trials at each site.
[a,b]Individual rings from the same numbered set were collected in the same drag.
[c] The three rings collected on day 2 at Portarlington (X 4) were from the same numbered set, but the 2cm ring was recovered by a different vessel from the other two.

	St. Leonards					Dromana					Portarlington East X 2					Portarlington East X 4				
Depth of rings (cm)	0	2	4	6	8	0	2	4	6	8	0	2	4	6	8	0	2	4	6	8
Day 1	-	0	0	0	0	7[a]	1[a]	1[a]	0	0	0	0	0	0	0	0	0	0	0	0
Day 2	-	1[b]	0	1[b]	0	1	0	0	0	0	1	0	0	0	0	1[c]	1[c]	1[c]	0	0
Day 3	-	5	2	0	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total Recovered	-	6	2	1	0	8	1	1	0	0	1	0	0	0	0	1	1	1	0	0
Total Deployed	0	32	32	32	32	33	33	33	33	33	38	38	38	38	38	37	38	38	38	38

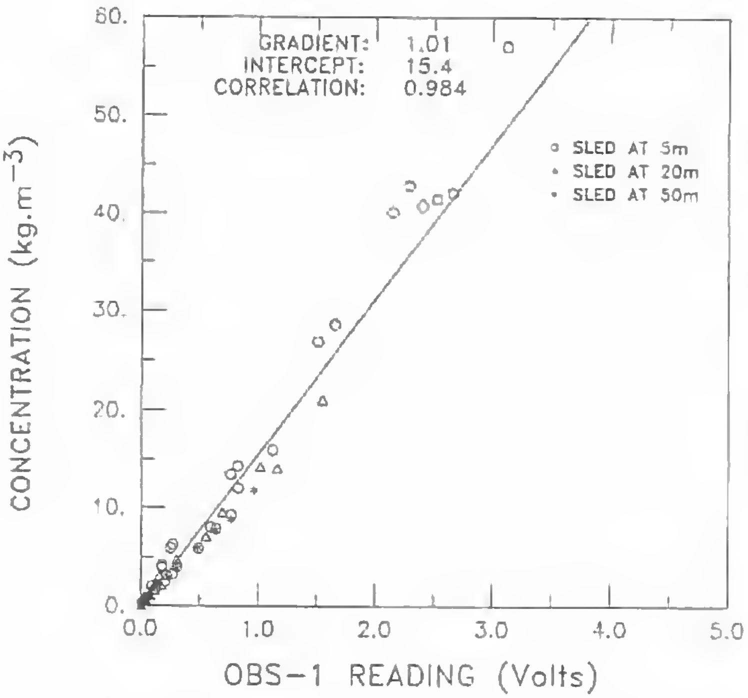

FIG.11. Sediment concentrations from water samples collected at 5, 20 and 50 m behind a Peninsula scallop dredge versus the turbidity sensor reading at Dromana.

cally disturbs the top 10–20mm of sediment, but that dredges sometimes disturb a layer up to 60mm thick. Predictions of sediment concentrations based on these estimates of the depth of sediment disturbance are similar to measured concentrations. Measurements at Dromana indicate that the plume extends about 1m above the bed immediately behind the dredge. Sediment concentration at the bed is c.1600 kg.m^{-3}, after applying a pore volume correction factor of 0.6 to a density of 2650 kg.m^{-3}. Thus, if a layer of sediment 1.5cm thick is disturbed and redistributed throughout a 1m height, then it will be 'diluted' 66 times, giving a sediment concentration of 24kg.m^{-3}, i.e. 1600/66. This measurement is in accordance with that 5m behind the dredge, although measurements as high as 58kg.m^{-3} were observed (Fig.11).

DISCUSSION AND CONCLUSIONS

Measurements of the sediment concentration behind the dredge define the characteristics of the plume and the depth of disturbance. This information can be used to assess the magnitude and spatial extent of sediment disturbance by dredging and can be generalised to other sea bed types and grain size distributions. Thus, the measurements can be used to assess the potential environmental impact of scallop dredging. Impacts may be local physical changes that directly impact on biota (Currie & Parry, this memoir) or far-field changes, such as elevated turbidity that may impact on seagrass or reef communities.

Natural suspended sediment concentrations during storms were 2–3 orders of magnitude smaller than the concentration recorded immediately behind a scallop dredge. The dredging- related concentrations returned to natural storm levels after about 9 minutes at sites 60 and 80m downcurrent of the nearest boundary of experimental dredging plots, although the concentrations were still nearly an order of magnitude greater than those occurring during the more common storm intensities. While a plume may be visually observed behind a dredge for longer than 9 minutes, the plume at these times will consist of fine sediments. Some of the finest sediments may take a considerable time to settle; the time would depend on the prevailing weather and the grain size. By disturbing the fine material, dredging may cause a significant redistribution of fine sediments within the Bay. In addition, the dredging may break natural sediment bonds (cohesiveness and biological bonding), causing increased likelihood of renewed suspension during natural storms.

Any direct environmental impact of the plume is likely to be small. However, the restricted spatial extent of the bulk of the deposition will result in localised high sedimentation. The measurements provide a quantitative estimate of the relative sediment concentrations during storms and dredging. However, a number of complexities in the natural system remain to be treated. For example, wave orbital motion is a strong function of water depth, and so more energy will be available at the bed for sediment entrainment around the margins of the bay than in the deeper central regions. Indeed, quantities caught by sediment traps in this program along a transect with depths ranging from 10–23m were about 50g in 10m depths compared with <10g in water 15m or deeper, for the same time period.

We are now using the data to confirm wave prediction theory and have established an annual distribution of wave energies throughout the bay. In conjunction with a numerical hydrodynamic model of the tidal and wind-driven current speeds (Black et al.,1993), a summary of the hydrodynamic energy available at the sea bed for sediment suspension at all sites in the bay is being created. With the grain size data, this provides the basis for an estimate of natural annually-averaged suspended sediment loads for direct comparison with the dredging data.

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APPENDIX

CALIBRATION OF TURBIDITY SENSORS

Turbidity sensors were calibrated using the techniques applied by Black & Rosenberg (1991) using, for comparison, a bed sediment sample and sediment captured in a trap elevated 0.35m above the bed. Differences between the two calibrations were related to differences between grain sizes in the samples and so we adopted the calibration using suspended sediments rather than the bed sediments.

For validation, two sets of pumped suspended sediment samples were obtained using a 'March' 12V submersible electric pump attached to SEDCAM by divers. These were located 60 m downstream of experimentally-dredged plots. The concentrations derived from pumped samples and from sensors exhibit acceptable agreement (Fig.12), particularly at Portarlington. The larger deviation at St Leonards is probably a sample handling effect, related to pre-drying of samples, or a grain size effect. The grain size of sediments captured in sediment traps during storms used in the calibration will differ from that observed downstream of the experimental dredging.

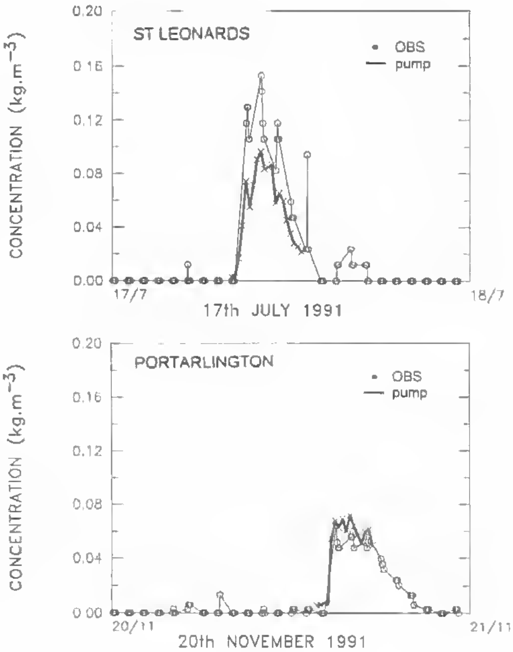

FIG.12. Comparison of sediment concentrations taken from pumped water samples and concentrations from the OBS turbidity sensors at 35 cm above the bed. The sites were downstream of experimental dredging plots at St Leonards and Portarlington.